Highlights

- Wearable trackers have acceptable accuracy, especially for measuring step counts, moderate to vigorous physical activity~~MVPA,~~ ~~ECG~~ and ~~HR~~heart rate, and for electrocardiography, but not for measuring respiratory rate ~~(RR)~~.
- Most older adults have reported ease of use and also demonstrated high-level adherence over daily long-term use.
- Methodological designs for data collection ~~were~~ have been heterogeneous and currently there are no standardised methods for quantifying data from wearable devices in older adults. ~~As such f~~
- Frameworks and ~~/~~ or guidelines~~,~~ are needed to support the ongoing use of wearable trackers to capture the physical activity of older adults.

~~Data management and~~The use of wearable trackers ~~in~~ by older adults and data management: A systematic review.

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Abstract

Background: Wearable trackers as research or clinical tools are increasingly used to support the care of older adults, due to their practicality in self-monitoring and potential to promote healthy lifestyle behaviours. However, there is limited understanding of appropriate data collection ~~methods~~ and analysis ~~for~~ methods in different contexts ~~still exists~~.

Aim: To summarise evidence on wearable data generation and management in older adults, focusing on physical activity (PA), electrocardiogram (ECG), and vital signs monitoring. In addition to examine the accuracy and utility of ~~incorporating~~ wearable trackers in~~to~~ the care of older people.

Methods: A systematic search of CINAHL, MEDLINE, PubMed and a manual search were conducted. Twenty studies ~~targeting~~ on the use of wearable trackers ~~use~~ by ~~in~~ older adults met the inclusion criteria.

Results: Methodological designs for data collection and analysis were heterogeneous, with diverse definitions of wear and no-wear time, the number and type of valid days, and proprietary algorithms. Wearable trackers had adequate accuracy for measuring step counts, moderate to vigorous physical activity (MVPA), ECG and heart rate (HR), but not for respiratory rate. Participants reported ease of use and had high-level adherence over daily long-term use. Moreover, wearable trackers encouraged users to increase their daily ~~PA~~ level of physical activity and decrease waist circumference, facilitating atrial fibrillation (AF) diagnoses and predicting length of stay.

Conclusion: Wearable trackers are multi-dimensional technologies offering a viable and promising approach for sustained and scaled monitoring of older people’s health. Frameworks and/or guidelines, including standards for the design, data management and application of use specifically for older adults, ~~is~~ are required to enhance validity and reliability.

Keywords

older, physical activity, wearable, sensor, monitor, tracker

1. Introduction

Aging populations with their high prevalence of chronic diseases have a significant impact on the healthcare system of any country. Fortunately, extraordinary advances in wearable tracker technology promote the potential to meet the demands of the healthcare system and facilitate the care of older adults. Notably, a wide array of commercial wearable trackers have recently appeared on the market. These trackers are inexpensive and are equipped with advanced functionality that utilises proprietary sensor technologies and data processing formulas to offer users a real-time assessment of their physiological, physical, psychological, and behavioural data [1, 2]. This includes data on heart rate (HR), blood pressure (BP), respiration rate (RR), electrocardiogram (ECG), and physical activity (PA) levels [1, 2]. Therefore, wearable trackers offer a practical alternative for everyday monitoring of PA, ECG and vital signs [2].

Although older adults perceive wearable trackers as beneficial and acceptable [3], the fast advances in wearable technology and the diverse methods of data processing have resulted in a lack of standards of practice for monitoring calibration and validation and field application, such as for the objective monitoring of PA [4]. Specifically, how to collect, calibrate, process, and use data from wearable trackers continues to be one of the critical challenges when using these devices [4]. It is also important to note that accelerometry assumptions for the selection of cut-points and data analysis are not standardised across research protocols [5, 6]. Most research guiding accelerometry data analysis methods is derived from studies that involved children and young adults [5, 7, 8], and there is limited research on accelerometry data in older adults[6]. Consequently, the primary aim of this paper is to present a systematic review of wearable data generation and management in older adults focusing on PA, ECG and vital signs monitoring (i.e., HR, BP, and RR). The secondary aim is to examine accuracy and the utility of incorporating wearable trackers into the care of older adults.

2. Methods

Both an electronic database search of CINAHL, MEDLINE, PubMed and a manual search were performed to identify the relevant articles. The search included the following terms: (1) 'sensor' or 'monitor' or 'device or 'tracker', and (2) 'wearable'. We limited our search to adults aged 65 years and older using relevant Medical Subject Headings. We included studies which met the following criteria: (1) published in English and targeted older population (i.e., ≥ 65 years old), (2) specifically investigated health-related wearable trackers; (3) study outcome focused on PA (i.e., active minutes and step counts), ECG, and vital signs monitoring. We excluded studies that primarily involved traditional pedometers or research grade trackers such as the ActiGraph accelerometer. We also excluded studies that mainly examined 'gait' and 'falls' because a recent published review[9] has already summarised the current literature on older adult's gait assessment through use of wearables.

Using the above keywords, the initial search retrieved 485 studies of which 20 were eligible for full review (Figure 1). Any disagreements about inclusion were resolved through conversation between two team members (MA and RG). The Critical Appraisal Skills Programme (Cohort Study) Checklist was used to assess the quality of the reviewed studies. On assessment, although five of the studies met a minimum 80% of the evaluation criteria, the majority of the included studies were of poor to moderate quality. The findings of the reviewed studies were extracted manually and summarised in tables.

3. Results

3.1 Overview of the wearable trackers included in the reviewed studies

Twelve different wearable trackers and 20 studies were included in this review (Table 1). Trackers include: ADAMO Care Watch, Fitbit Charge HR, Fitbit Flex, Fitbit One, Fitbit Zip, HealthPatch MD, iRhythmZio, Jawbone UP, MagIC, Misfit Shin, Nike+FuelBand, and Polar A300. The most commonly used wearable trackers across all reviewed studies were Fitbit One (n=7) and Fitbit Charge HR (n=4). It should be noted, there is a high turnover rate of wearable trackers available on the market so that one of the trackers reviewed, Jawbone UP, discontinued in 2011.

3.2 Data acquisition in the reviewed studies

The sample characteristics of the 20 included studies, wearable tracker name, data collection method, and analysis protocols are summarised in Table 2. The majority of the reviewed studies had PA as their focus (n=15), followed by ECG (n=3) and then vital signs (n=2).

The sample sizes ranged from eight to 2659 (total 3741 participants). The overall mean age was 69 years and almost all studies (n=18) included both males and females, with the minority of participants, females (42%). The diagnoses varied widely among the studies, but almost half the studies (n=8) included participants who had or were at high risk of cardiovascular disease. Twelve studies were conducted in a free-living environment, 6 studies were conducted in a controlled environment, and 2 studies utilised both controlled and free-living environments. The wearable trackers were placed on the wrist (n=12), waist (n=8), chest (n=4), ankle (n=2) and pocket (n=2).

Data collection, and analysis protocols were heterogeneous. The overall duration of the data collection ranged from two minutes to eight months. Among the studies conduction in a free-living environment, the tracker wear time was during all waking hours (i.e. valid day with ≥10 wear hours/day) in three studies, and for 24 hours in 11 studies. The definition of wear time varied among the reviewed studies. For instance, a cut-off threshold of 150 minutes [10] or 60 minutes [11] of continuous zero data from the wearable tracker was deemed as being non-wear data. Participants were required to wear the tracker for at least seven consecutive wearing days in over half of the included studies (11 of 20); at least five consecutive wearing days in one study; at least four consecutive wearing days including weekend days and weekdays in one study; with the remaining studies (7 of 20) including three consecutive wearing days or less. The algorithms and classifiers used for the feature computation varied among the reviewed studies. The majority of studies utilised proprietary algorithms that set its sampling interval at 60 seconds, but the shorter epochs (15 seconds) were reported in one study. Similarly, almost all of the studies used proprietary algorithms (not known to the authors, as the formulas are proprietary to the company) to define the cut point of the measured outcomes; for example, minutes of moderate to vigorous physical activity (MVPA). Two studies utilised clinicians (e.g., cardiologists) to manually score and classify the data.

3.3 Data accuracy: Outcomes of the reviewed studies in terms of reliability and/or validity

Twelve [1,10,23,26-29,31-33,38-39] of the 20 reviewed studies targeted validity and/or reliability (Table 3). Overall, eight studies examined the validity and/or reliability of different wearable trackers in measuring step counts [10,26-29,32,33]. The outcomes of these studies supported the validity and reliability of the wearable trackers in tracking step counts but noted that walking at slow speeds and wrist-worn trackers may affect their accuracy. Two studies highlighted the capabilities of wearable trackers in accurately tracking active minutes of PA, especially MVPA [30,31]. Similarly, two studies showed wearable trackers had acceptable validity for measuring HR [38,39]. One study found that wearable trackers provide an accurate ECG reading [23]. However, one study warned against the use of wearable trackers for measuring respiratory rate as its accuracy was outside acceptable limits [38].

3.4 Data utility: Outcomes of the reviewed studies regarding the clinical benefits of wearable trackers and their acceptability

Eight of the 20 reviewed studies targeted the data utility of wearable trackers (Table 4). Four [24-25,34,37] of the eight studies centred focused on the usefulness of wearable trackers as a measure of clinical outcomes, three studies [3,11,34] focused on the participants' acceptance, adoption or abandonment of wearable trackers, one study [36] included both of the aforementioned aims, and one study examined the usefulness of wearable trackers as a motivational tool for PA behaviour change.

Regarding the clinical benefits, one study found a significant relationship between steps taken, length of stay, and dismissal disposition [37]. One study showed self-monitoring of PA using wearable trackers decreased waist circumference significantly [35], and two studies highlighted that wearable self-applied ECG patches facilitated AF diagnoses [24,25]. Moreover, one study [36] showed that feedback from a PA wearable tracker motivates behaviour change. Regarding the wearable tracker acceptability, three [3,11,35] studies found that participants reported the wearable trackers were easy to use and they also had high-level adherence over daily long-term use. However, one study [34] found that abandonment-related issues influencing daily long-term use of wearable trackers involved the collection of inaccurate data, time wasting, and wearing discomfort.

4. Discussion

Our results showed that overall, wearable trackers had adequate accuracy, especially for measuring step counts, MVPA, ECG and HR, but not for measuring RR. Moreover, most participants reported ease of use and also demonstrated high-level adherence over daily long-term use. Some participants, however, found the wearable trackers very difficult to use, and it is therefore important to consider the usability, comfort and feasibility of the trackers for older participants. Importantly, wearable trackers have become standard objective methods for assessing health outcomes such as PA. They have also demonstrated the usefulness of wearable technology for encouraging users to increase their daily PA level and to decrease their waist circumference, facilitating AF diagnoses and predicting hospital length of stay [24, 35, 37]. Therefore, wearable trackers may be promising for use among this cohort to help in diagnosing, monitoring and encouraging sustained changes in healthy behaviours such as PA.

Importantly, our findings highlighted that methodological designs for data collection were heterogeneous and that there is no standardised method for quantifying data from wearable devices in older adults. Given the lack of a universally accepted definition [12, 13] for data collection and analysis of wearable trackers, future research is needed to produce specific assumptions for this work that is most applicable for older people, particularly accounting for their physical capacity. It is vital to standardise tracker placement and the number and type of valid days needed to achieve acceptable validity and reliability to ensure comparability across study outcomes. For example, the most common practice for PA measurement is a minimum of four days of valid data for analysis, including weekend days [14]. It is also critical to standardise the definitions of wear time and no-wear time. For instance, the criteria for no-wear time most commonly applied is removal of the tracker for 60 minutes or more of continuous zeros, with allowance of 1-2 minutes [15], but 90 minutes has been proposed for older people with limited mobility [16].

Of note, almost all the review studies relied on tracker proprietary algorithms, which set the sampling interval at different short or long epochs. Thus, a standardised algorithm or cut points to define an outcome (e.g. MVPA) are critical to support the tracker validity and reliability. A considerable amount of time and effort has been invested by researchers and manufacturers to make sure the algorithms in wearable trackers accurately measure clinical outcomes such as PA level. However, this pursuit presents numerous issues and challenges for stakeholders; namely, clinicians, researchers, tracker manufactures and patients [1]. Algorithms to aggregate raw tracker data into operational variables are regularly modified and frequently not available [17]. For instance, the Fitbit manufacturer recently modified the algorithm used to count active minutes without notification. All stakeholders are therefore eager to ensure tracker accuracy facilitates the precise monitoring of PA and other important health outcomes. Hence, wearable tracker manufacturers need to ensure the algorithm delivers high-level accuracy equal to research-grade accelerometers (e.g. Actigraph) and to inform stakeholders when modifications to the algorithms occur to uphold their trust.

There are difficulties in ensuring the literature remains up to date on current models due to the frequency of new releases of wearable trackers[17]. Moreover, consideration must be given to the high turnover rate of wearable trackers in the market and that some trackers are no longer produced (e.g. Jawbone). The wide range of tracker features (e.g. step counts, active minutes and energy expenditure) also complicates the practicality and accuracy of wearable trackers in measuring health outcomes such as all dimensions of PA [17]. Uncertainties around the ownership of data and therefore accessibility to the data for research purposes also presents challenges to review boards in institutions as essentially it is data collection from third parties [1, 18]. In addition, there are issues regarding data structure and quality due to tracker manufacturers not sharing the data or their data collection methods with researchers [1, 18, 19]. Lastly, given we live in the digital personal health era, issues may emerge over data privacy [1, 18]. Hence, future research is needed to generate studies on privacy policies of wearable trackers and also to review federal and state legislation related to data protection.

Notably, the acceptable level of inaccuracy varied and often was not clearly defined. Indeed, even in the literature there is no widely agreed definition of acceptable degree of error for PA wearable trackers. Acceptable measurement error for PA under controlled conditions or for research purposes is suggested to be within ±3% [20, 21], and under free-living conditions is within ±10% [20, 21]. Other literature advises that errors of less than 20% have acceptable validity for clinical purposes [22]. Depending upon the work being studied and the purposes of the validation study, it is important for future studies with elderly participants to standardise the analysis methods in order to guide validity interpretation for wearable trackers and to highlight the different validity criteria between the tested and criterion measures for clinical purposes compared to research purposes. Finally, it is worth noting that gender differences are likely, yet seldom examined. Only one study [30] analysed data separately by gender using Fitbit-Flex noted that male participants recorded significantly more steps and higher MVPA minutes than their female counterparts.

Several limitations need to be acknowledged. We searched only a limited number of databases and reviewed articles published in English only so some studies may have been missed. Also, there is insufficient reporting for the accelerometry assumptions in several of the reviewed studies, creating difficulty for fully evaluating the accelerometer protocol.

5. Implications for practice and future research

The findings of this review have a number of important implications:

1. Wearable trackers are generally valid, reliable and/or feasible when tracking step counts, MVPA, ECG and HR in aging populations. Thus, trackers may be ideal to help in diagnosing, measuring, monitoring and/or motivating in this population cohort.
2. There needs to be a framework and/or guidelines and a standardised method for the collection and analysis of wearable tracker data specifically for older people's physical capacity.
3. Manufacturers of trackers must ensure the tracker algorithm delivers a high level of accuracy similar to a research-grade accelerometer.
4. Although there is extensive validity and reliability research available, there are no studies examining the responsiveness of wearable trackers. Thus, further research is needed to develop evidence-based responsiveness.

6. Conclusion

A definitive recommendation for a wearable tracker or method of data collection and analysis could not be made due to lack of strong evidence as the majority of primary studies used proprietary algorithms and there is no way to access the primary data. However, wearable trackers are generally valid, affordable and useful for monitoring a number of clinical outcomes such as PA, ECG and vital signs in real-time, and for accounting for day-to-day variations. This encourages more accurate and personalised clinical intervention for older people. Wearable trackers are promising tools for clinicians to manage the care of older people, however, the validity and reliability of wearable trackers are impacted by a number of factors including fast-paced technological developments, frequent updates to algorithms by manufacturers, and an absence of a consensus protocol for data collection and analysis. Future research is encouraged to develop guidelines and standards for the design and application of wearable technology in aging populations.

Contributors

Muaddi Alharbi contributed to the concept, design and conduct of the review, analysis and writing of the manuscript.

Nicola Straiton contributed to the concept and design of the review, and writing of the manuscript.

Sidney Smith contributed to the analysis and writing of the manuscript.

Lis Neubeck contributed to the analysis and writing of the manuscript.

Robyn Gallagher contributed to the concept and design of the review, analysis and writing of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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Figure 1. Search Strategy

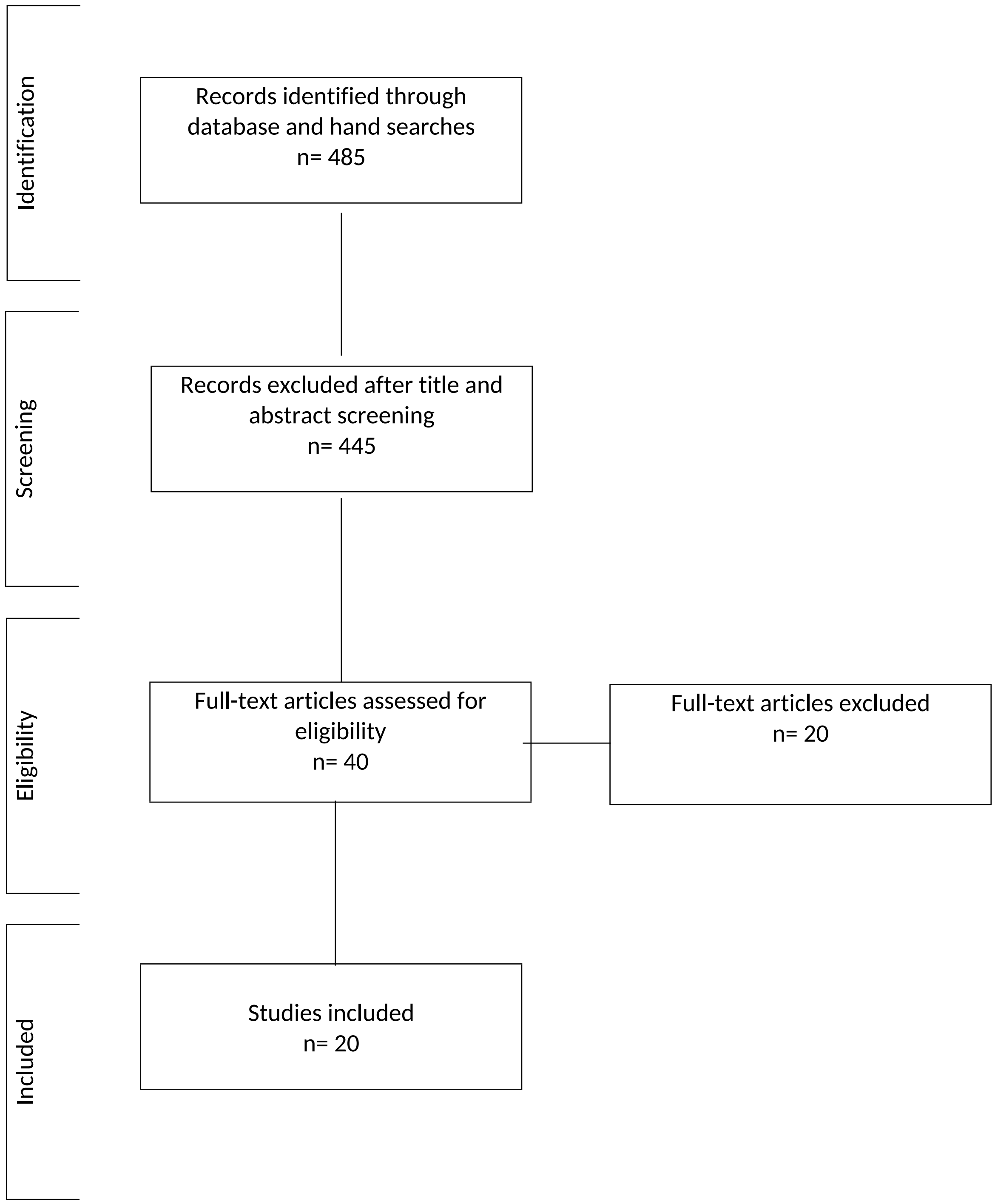

Table 1: Wearable trackers included in the review

Tracker	Released date	What is measured	Software	Battery life
ADAMO Care Watch	2010	Steps, distance, calories, active minutes	On screen summary online-feedback, also phone apps	21 days
Fitbit Charge HR	Jan 2015	Steps, distance, calories, active minutes, sleep, HR	On screen summary online-feedback, also phone apps	5 days
Fitbit Flex	May 2013	Steps, distance, calories, active minutes, sleep	Online-feedback, also phone apps	7–10 days
Fitbit One	Sep 2012	Steps, distance, calories, active minutes, sleep	On screen summary online-feedback, also phone apps	14 days
Fitbit Zip	May 2013	Steps, distance, calories, active minutes, sleep	On screen summary Online-feedback, also phone app	4–6 months
HealthPatch MD	Jan 2015	Single-Lead ECG, HR, HR Variability, vital signs, fall detection, steps	Online-feedback, also phone apps	3-5 days
iRhythmZio^{XT}	Jan 2011	Single-Lead ECG, HR	Online-feedback, also phone apps	14 days
Jawbone UP	Nov 2011 (Note: Dec 2011 discontinued)	Steps, calories, distance, sleep	Online-feedback, also phone apps	10 days
MagIC: a textile-based wearable system	April 2009	ECG, respiratory frequency and motion	Online-feedback, also phone apps	3 days
Misfit Shine	Dec 2013	Steps, distance, calories, active minutes, sleep	Online-feedback, also phone apps	4-6 months
Nike+ FuelBand	Nov 2013	Steps, calories	Online-feedback, also phone apps	4 days
Polar A300	Feb 2015	Steps, distance, calories, active minutes, sleep, HR	On screen summary Online-feedback, also phone apps.	26 days

Table 2: Summary of data acquisition in the reviewed studies: wearable specific population, data collection, and analysis details

Authors / setting	Sample	Wearable tracker	Wearable locations	Measure(s) tested	Data collection setting	Instructions for wear	Data collection	Epoch used for analysis	Data cleaning	Cut points
ECG										
Di Rienzo et al.[23] Italy	N = 50 CR patients Age:67 Female: 0	MagIC: a textile-based wearable system	Chest	Cardiac rhythm and arrhythmic events	Controlled	Wear at all times during the test	60m for each participant	200Hz	NR	Data manually scored by two cardiologists
Steinhubl et al.[24] USA	N = 2659 at risk of AF Age:73 Female: 1026 (39%)	iRhythmZio	Chest	ECG patch facilitated AF diagnosis	Free-living	Wear patch for up to 2 weeks	During first and last 2 weeks of 4-month period beginning immediately or 4 months after enrolment, respectively	30s	Individuals in monitored cohort not wearing a patch were assumed not to have AF unless identified via claims data as having AF	Incidence of newly diagnosed AF defined as ≥30 seconds of AF or flutter detected by tracker
Turakhia et al.[25] USA	N = 75 at risk of AF Age:70 Female: 0 (0%)	iRhythmZio	Chest	ECG patch facilitated AF diagnosis	Free-living	Wear patches for up to 2 weeks	14 days of uninterrupted monitoring	30s	Excluded data for repeated or subsequent Zio Patch monitoring to minimize confounding by indication	Each AF episode defined as presence of ≥30 seconds of continuous AF during monitoring. Cardiovascular technicians confirm and classify arrhythmia diagnoses

PA										
Magistro et al.[26] Italy	N = 20 older participants Age:75 Female 10 (50%)	ADAMO Care Watch	Wrist	Steps	Controlled	Wear at all times during the test	Procedure took 60m	50Hz	A step was defined as a negative slope of the combined acceleration pattern when acceleration curve crossed below dynamic threshold	The dynamic threshold level was estimated via the max. and min. values of the bursts retrieved, and the average value, (max + min) divided by 2
Burton et al.[27] Australia	N = 31 older participants Age:74 Female 20 (65%)	Fitbit Flex Fitbit Charge HR	Wrist	Steps	Controlled and free-living	Wear for 14-days including sleeping	7 days; direct observation on days 1 and 7 14 days; 24h for free-living period	60s	Missing data eliminated in the analysis	Used proprietary algorithms
Paul et al.[28] Australia	N = 32 older participants Age:68 Female: 20 (63%)	Fitbit One Fitbit Zip	Waist	Steps	Controlled and free-living	Wear during a 2m walk test (2MWT) and then wear them during waking hours	2m for each participant 7-day; during waking hours	60s	No definition for wear time. Data checked against participants' activity logs for inconsistencies - erroneous data removed	Used proprietary algorithms
Simpson et al.[29] Canada	N = 42 older adults Age:72 Female: 32 (74%)	Fitbit One	Waist Ankle	Steps	Controlled	Wear during walking for a distance of 15m with 8 different walking trials	During a single testing session	60s	NR	Used proprietary algorithms

Alharbi et al.[30] Australia	N = 48 CR patients Age:66 Female:23 (48%)	Fitbit Flex	Wrist	Steps & MVPA	Free-living	Wear tracker during waking hours	4 consecutives days (2 weekend days and 2 week days) during waking hours	60s	Valid day at least 10h from time awoke in morning until time to bed at night	Used proprietary algorithms
Boeselt et al.[31] Germany	N = 20 Patients with chronic obstructive pulmonary disease Age:66 Female:3 (15%)	Polar A300	Wrist	Calories, daily activity time (h) and METS	Free-living	Wear at all times.	3 consecutive days, 24h	60s	100% of sample above crucial number of steps/day, activity tracker comparison data in all patients.	• Light- activity = 1.1 to 2.9 METs • Moderate-activity = 3.0 to 5.9 METs • Vigorous-activity = 6.0 or > METs
Floegel et al.[32] USA	N = 99 older participants Age:79 Female:25 (71%)	Fitbit One Fitbit Flex Jawbone UP	Waist Wrist Waist Wrist	Steps	Controlled	Wear at all times during the test	During a single testing session	60s (Fitbit) 30Hz (Jawbone UP)	NR	Used proprietary algorithms
Thorup et al.[33] Denmark	N = 24 Cardiac patients Age:67 Female:2 (8%)	Fitbit Zip	Waist	Steps	Free-living	Wear at all times during free-living activities	1 day; 24h (during hospitalisation) and 4 weeks; 24h (thereafter at home; mean 28.2, range 26–31)	60s	NR	Used proprietary algorithms
Farina et al.[10] UK	N = 25 Cardiac patients Age:73	Misfit Shine	Waist Wrist	Steps	Free-living	Wear during waking hours (except for water-based activities)	7 consecutive days, during waking hours	60s	Non-wear data: A cut-off threshold of 150m of	Used proprietary algorithms

	Female:12 (48%)	Fitbit Charge HR	Wrist						continuous zero data A valid day: at least 10h/day. Minimum of 4 days of valid data required for inclusion in analysis	
Speier et al.[11] USA	N = 200 Cardiac patients Age:65 Female: NR	Fitbit Charge HR	Wrist	Adherence to wearable tracker based on sedentary, Active minutes, and non-wear time	Free-living	Wear at all times	Over 90 days, 24h	60s	A valid day: at least 10h/day Non-wear time: NHANES). estimated using continuous bouts of zero activity counts lasting longer than 60 minutes, allowing for up to two minutes of activity. Determined by HR at hour (HR-h) or minute (HR-m) level	Used proprietary algorithms
Fausset et al.[34] USA	N = 8 older participants Age:65 Female: 4 (50%)	Fitbit One Nike+ FuelBand	Pocket Pocket Wrist	Attitudes toward PA monitoring technology	Free-living	Wear at all times	2 weeks	60s	NR	Used proprietary algorithms

McMahon et al.[3] USA	N = 95 older adults Age:70 Female: 71 (75%)	Fitbit One	Waist	Attitudes toward PA monitoring technology	Free-living	Wear at all times	Throughout 8-month study	60s	2 users dropped out after acutel illness.	Used proprietary algorithms
O'Brien et al.[35] USA	N = 34 older adults Age:74 Female: 22 (65%)	Nike+ FuelBand	Wrist	Steps, calories	Free-living	Wear at all times	12-week;, daily for 24h a day	60s	5 of the 34 participants dropped out because they did not want to wear the activity tracker every day	Used proprietary algorithms
Kanai et al.[36] Japan	N = 55 inpatients with ischaemic stroke Age:65 Female: 28 (51%)	Fitbit One	Waist	Steps; light, moderate, and vigorous PA	Free-living	Wear at all times	Daily; 24h until discharge from supervised rehabilitation 5 to 6 times/week. Mean length of hospital stay 11 to 12 days	60s	PA defined at baseline as day 2 after enrolment because patients did not wear accelerometer for 24h on day 1	Used proprietary algorithms
Cook et al.[37] USA	N = 149 a postop. cardiac surgical patients Age:68 Female:66 (44%)	Fitbit One	Ankle	Steps	Free-living	Trackers placed on patients' ankles after transition from ICU	Daily for 5 days (LOS)	60s	Two participants died and excluded from analysis	Used proprietary algorithms
Vital signs										
Breteler et al.[38] Netherlands	N = 25 postoperative surgical patients Age:65	HealthPatch MD	Chest	Respiratory and heart rate	Controlled	Attached at all times during the test	1–3 days; 24h	15m	Empty or invalid data (not-a-number) removed to	bradycardia (HR <50 beats/m), tachycardia HR >100 beats/m),

	Female 7 (28%)								obtain continuous 2D vectors of vital sign samples with corresponding time stamps	bradypnoea (RR <12 breaths/ m) and tachypnoea (RR >20 breaths/m)
Kroll et al.[39] Canada	N = 50 ICU patients Age:65 Female: 24 (48%)	Fitbit Charge HR	Wrist	HR	Controlled	Wear at all times	One day; 24h	60s	Trackers not reassessed for duration of 24h recording period. High frequency data captured from continuous bedside monitoring to provide accurate gold standard assessment of HR and analysed tracker performance on both pooled and per-patient level	Used proprietary algorithms

CR = cardiac rehabilitation; ECG = Electrocardiography; PA = physical activity; AF = atrial fibrillation; LOS = length of stay; ICU = intensive care unit; METs = metabolic equivalent tasks; NR = not reported; h = hours; m = minutes; s = seconds; Hz = hertz

Table 3: Data accuracy: Outcomes of the reviewed studies in terms of reliability and/or validity

Authors	Data collection settings/methods	Data comparison time/ distance	Wearable tracker	Measure(s) tested	Cross-validation measure	Main conclusions
Magistro et al.[26]	Controlled Performed several randomly ordered tasks: walking at slow, normal and fast self-paced speeds; a Timed Up and Go test (TUG); a step test and ascending/ descending stairs	Procedure took 60m	ADAMO Care Watch	Steps	Steps observed and counted with a manual tally counter	ADAMO Care Watch demonstrated highly accurate measurements of steps count in all activities, particularly walking at normal and slow speeds
Burton et al.[27]	Controlled and free-living 2MWT: walk without assistance as fast and safe as permissible for 2m. Free-living activities	7 days; direct observation on day 1 and 7 14 days; 24h for free-living period	Fitbit Flex Fitbit Charge HR	Steps	Visual step count (video recording) GENEactiv accelerometer	Good reliability and validity of the Flex and ChargeHR, however both trackers underestimated step count in the laboratory environment
Breteler et al.[28]	Controlled Attached both the wireless sensor and bedside routine standard for at least 24h	1–3 days; 24h	Health Patch MD	Respiratory and heart rate	XPREZZON: ICU grade' patient monitoring system.	Accurate measurement of HR, but not for respiratory rate
Kroll et al.[39]	Controlled Continued to collect data for the full 24h period	One day; 24h	Fitbit Charge HR	HR	BedMaster-EX, Excel Medical, Jupiter: ICU bedside continuous ECG monitors	Tracker–derived HRs were slightly lower than those derived from continuous ECG monitoring in real-world testing and not as accurate as pulse oximetry- derived HRs
Di Rienzo et al.[23]	Controlled In 20 patients with severe clinical conditions, recording was 30m while subjects at rest in bed in the hospital cardiac unit	60m for each participant	MagIC: a textile-based wearable system	Cardiac rhythm and arrhythmic events	Fukuda Denshi telemetric ECG (mod DS 5700, Tokyo, Japan): Traditional ECG tracker:	In static condition MagIC accurate in monitoring cardiac rhythm and arrhythmic events and comparable to that obtained by a traditional one-lead ECG recorder. During

	With remaining 20 patients, ECGs were performed for 36m during physical rehab. sessions according to protocol: at rest (4m lying, 1m standing), during mild calisthenic PA (10m), while pedalling a cycloergometer (15m) and during a 6MWT.					movement MagIC provides an ECG signal of better quality
Paul et al.[28]	Controlled and free-living Wore trackers simultaneously during a 2MWT and then during free-living activities	2m for each participant 7-day; during waking hours	Fitbit One Fitbit Zip	Steps	ActiGraph Visual step count (2MWT)	Fitbit accurately tracked steps during the 2MWT. There was strong agreement between Fitbit and ActiGraph counted steps
Simpson et al.[29]	Controlled Participants walked a distance of 15 metres for 8 different walking trials	During a single testing session	Fitbit One	Steps	Visual step count (video recording)	Fitbit accurately captured steps at slow speeds when placed at the ankle
Alharbi et al.[30]	Free-living Wear both trackers simultaneously during free-living activities	4 consecutives days (two weekend days and two weekdays) during waking hours	Fitbit Flex	Steps MVPA	ActiGraph	Fitbit- is a valid, reliable and alternative tracker for activity monitoring specific to predicted attainment of PA guideline recommendations for step counts and minutes of MVPA)
Boeselt et al.[31]	Free-living Wear at all times during free-living activities	3 consecutive days; 24h	Polar A300	Calories, daily activity time (h) and METS	Bodymedia SWA	Polar tracker equivalent to SWA for assessment of PA time, step count and calorie consumption in COPD patients
Floegel et al.[32]	Controlled	During a single testing session	Fitbit One Fitbit Flex	Steps	StepWatch	StepWatch, Fitbit One, and Jawbone UP

	Instructed to walk at self-selected pace along an unobstructed 100 metre predetermined, flat marked route at their respective community centre location		Omron HJ-112, Jawbone UP		(direct observation through continuous videography)	accurate at measuring steps
Thorup et al.[33]	Free-living Wear at all times during free-living activities	1day; 24h (during hospitalisation) and 4 weeks; 24h (thereafter at home mean 28.2, range 26–31)	Fitbit Zip	Steps	Shimmer3	A speed of 3.6 km/h or higher is required for acceptable accuracy in step measurement using Zip. Inaccuracies directly related to slow speeds, and thus for patients with cardiac disease who walk at a slow pace
Farina et al.[10]	Free-living Wear the trackers during waking hours (except for water-based activities)	7 consecutive days; during waking hours	Misfit Shine Fitbit Charge HR	Steps	Actigraph and NL2000	Compared to the ActiGraph GT3X+, the waist-worn Misfit Shine had highest agreement. Wrist-worn trackers showed poorer agreement to reference trackers

MWT = minute walk test; PA = physical activity; HR = heart rate; LOS = length of stay; ECG = electrocardiography; AF = atrial fibrillation; ICU = intensive care unit; IHD = ischemic heart disease; h = hours; m = minutes; Sensewear = SWA

Table 4 Data utility: Outcomes of the reviewed studies regarding the clinical benefits of wearable trackers and their acceptability

Authors	Research Focus	Objectives	Wearable tracker	Main conclusions
Speier et al.[11]	Acceptance, adoption or abandonment	Evaluate adherence rates using consumer-grade continuous-time HR and activity tracker over 90 days in a group of patients with IHD	Fitbit Charge HR	Using continuous-time activity trackers with HR monitors can be effective in a telemonitoring application, as patients had a high level of adherence (90% median usage) and low attrition (0.09% decrease per day) over a 90-day period.
Fausset et al.[34]	Acceptance, adoption or abandonment	Attitudes and usability issues were assessed and evaluated within a technology acceptance framework the Unified Theory of Acceptance and Use of Technology	Fitbit One Nike+ FuelBand	Initial attitudes were positive, but after using the tracker for two weeks, attitudes were mixed. 3 participants indicated they would continue using the tracker; whereas, 5 would abandon the tracker and described several issues including inaccurate data collected, wasting time, and uncomfortable to wear
McMahon et al.[3]	Acceptance, adoption or abandonment	To assess short and long-term experiences of Fitbit One in terms of acceptance, ease-of-use, and usefulness: domains in the technology acceptance model.	Fitbit One	91% agreed or strongly agreed that the tracker was easy to use, useful & acceptable both 10 weeks and 8 months after enrolling in the study. Ratings slightly dropped between these time points in all survey domains: ease-of-use, usefulness and acceptance
O'Brien et al.[35]	Acceptance & wearable trackers as useful measure of clinical outcomes	To evaluate the feasibility and utility of activity tracker use among older adults for monitoring activity, improving self-efficacy, and health outcomes	Nike Fuel	Participants found activity trackers easy to use, experienced a significant decrease in waist circumference. However no change in steps taken, calories burned, and self-efficacy
Kanai et al.[36]	Wearable trackers as a motivator of PA behaviour change	To evaluate the effect of accelerometer-based feedback on physical activity in hospitalized patients with ischemic stroke.	Fitbit One	Exercise training combined with accelerometer-based feedback effectively increased PA in hospitalized patients with ischemic stroke
Cook et al.[37]	Wearable trackers as useful measure of clinical outcomes	Examine an activity tracker to measure PA during hospital recovery after cardiac surgery.	Fitbit One	There was a significant relationship between the number of steps taken in the early recovery period, length of stay, and dismissal disposition
Steinhubl et al.[24]	Wearable trackers as useful measure of clinical outcomes	To determine effect of self-applied wearable ECG patch in detecting AF and the clinical consequences	iRhythmZio	Among individuals at increased risk for AF, use of home-based self-applied ECG patch facilitated AF diagnosis

Turakhia et al.[25]	Wearable trackers as useful measure of clinical outcomes	Screening for AF using continuous ambulatory ECG monitoring can detect silent AF in asymptomatic in patients with known risk factors	iRhythmZio	Tracker is feasible, with AF detected in 1 in 20 subjects with up to 2 weeks of monitoring. Also detected sustained atrial tachycardia and AF in 1 in 9 subjects

PA = physical activity; HR = heart rate; LOS = length of stay; ECG = electrocardiography;
AF = atrial fibrillation; ICU = intensive care unit; IHD = ischemic heart disease

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Conflict of interest

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